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INDUSTRIAL GEAR TRANSMISSION ERROR MINIMIZATION OPTIMIZATION GA ALGORITHM

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ABSTRACT

Today's competitive market required to optimize Weight and Volume of the gear design. Weight and Volume optimization of gear pairs is difficult to solve because it includes various objectives and large number of variables. Therefore, to solve such difficulty robust optimization technique will be useful to get optimal solution. Genetic algorithm will be useful to solve such difficulty using MATLAB. In this work a helical gear pair design optimization problem is solved. It is a multi-variable, complex non-linear problem with derived objective function and constraints. The objective is to minimize the volume of the gear. The design parameters considered are module, face width, number of teeth on drive and driven and helix angle. Results indicate that GA algorithm gives the best results for all design variables and objective function in helical gear design.

KEYWORD: MATLAB, Helical Gear, Genetic Algorithm, Constraints.

1. INTRODUCTION

1.1 General

Gear design is a complex phenomenon requiring consideration of several items such as gear geometry, material heat treatment, manufacturing, etc., to satisfy. Functional requirement, of high strength, high accuracy, low noise, and compactness of the drive. Traditionally, gear designers have been concerned with requirements of strength, noise, life, and accuracy of kinematic transmission. The recent focus of research however is the optimal design of compact gear pairs (gear boxes) for minimum weight and space requirements.

The problem of minimum volume design of simple gear trains has been a subject of considerable interest, since many high-performance power transmission applications (e.g., automotive, aerospace, machine tools, etc.) require low weight.

Gears plays an important role in transmit the necessary power for the proper function of the machines. The use of power is desirable at various angles to perform the various tasks like lifting, digging, cutting and pulling etc. This work describes the importance of helical gear in machinery and optimization of center distance using algorithm. The helical gears are employed to transmit motion between parallel shafts. These gears can also be used for transmitting motion between non-parallel, non-intersecting shafts. Helical gears are similar to spur gears except that the gears teeth are at an angle with the axis of the gears.

1.2 Helical gears

Helical gears are similar to spur gears except that their teeth are cut at an angle to the hole (axis) rather than straight and parallel to the axis like they are in the teeth of a spur gear. Helical gears are manufactured as both right and left-handed gears. The teeth of a left-handed helical gear lean to the left when the gear is placed on a flat surface. The teeth of a right-handed helical gear lean to the right when placed on a flat surface. In spur gears, the teeth are parallel to the axis whereas in helical gears Fig.1.1 (a) the teeth are inclined to the axis. Both the gears are transmitting power between two parallel shafts. [1] At any time, the load on helical gears is distributed over several teeth, resulting in reduced wear. When two helical gears are engaged as, the helix angle has to be the same on each gear, but one gear must have a right-hand helix and the other a left-hand helix. In helical gear the line contact is diagonal across the face of the tooth.

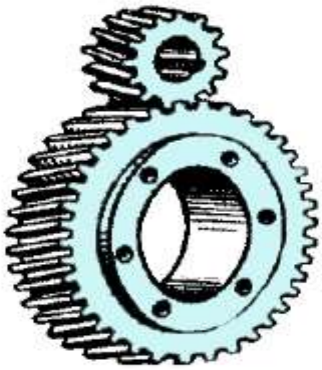


Fig.1.1: (a) helical gear

Hence gradual engagement of the teeth and the smooth transfer of load from one tooth to another occur. Helical gears are capable of providing smoother and quieter operations at the same time transmit heavy loads. They are useful for high speed and high power applications, quiet at high speeds. Helical gears operate with less noise and vibration than spur gears. At any time, the load on helical gears is distributed over several teeth, resulting in reduced wear. Due to their angular cut, teeth meshing results in thrust loads along the gear shaft.

1.3 The design process

The design of many engineering systems can be a complex process. Assumptions must be made to develop realistic models that can be subjected to mathematical analysis by the available methods, and the models must be verified by experiments. Many possibilities and factors must be considered during problem formulation. Economic considerations play an important role in designing cost-effective systems. Systems are used for engineering model to describe the design process.

The first step in the evolutionary process is to precisely define the specifications for the system. Considerable interaction between the engineer and the sponsor of the project is usually necessary to quantify the system specifications.

The second step in the process is to develop a preliminary design of the system. Various system concepts are studied. Since this must be done in a relatively short time, simplified models are used at this stage. Various subsystems are identified and their preliminary designs estimated.

The third step in the process is a detailed design for all subsystems using the iterative process described earlier. To evaluate various possibilities, this must be done for all previously identified promising concepts. The design parameters for the subsystems must be identified. The system performance requirements must be identified and satisfied.

1.4 Optimization techniques for optimum design problem

Modeling and optimization of process parameters of any manufacturing process is usually a difficult work where the following aspects are required: knowledge of manufacturing process, empirical equations to develop realistic constrains, specification of machine tool capabilities, development of an effective optimization criterion, and knowledge of mathematical and numerical optimization techniques. A human process planner selects the proper machining parameters using his own experience or from the handbooks. Performance of these processes, however, is affected by many factors and a single parameter change will influence the process in a complex way. Because of the many variables and the complex and stochastic nature of the process achieving the optimal performance, even for a highly skilled operator is rarely possible

2. ISSUES OF OLD ARTICLE

2.1 Gear Pairs Using Genetic Algorithm:

Y.K.Mogal: Up to now many optimization techniques have been developed & used for optimization of engineering problems to find optimum design. Solving engineering problems can be complex & time consuming when there are large number of design variables & constraints. A Gear design require the designer to compromise many design variables; i.e. continuous, discrete & integer variables in order to determine best performance of gear set. Therefore a conventional optimization technique has difficulty in solving those kinds of problem. In this paper Genetic algorithm is introduced for, 1] Minimization of power loss of worm gear mechanism with respect to specified set of constraints. 2] Minimization of volume of two-stage gear train.

Tae Hyong Chong: The design of gear train is a kind of mixed problems which have to determine various types of design variables; i,e., continuous, discrete, and integer variables. Therefore, the most common practice of optimum design using the derivative of objective function has difficulty in solving those kinds of problems and the optimum solution also depends on initial guess because there are many sophisticated constraints. In this study, the Genetic Algorithm is introduced for the optimum design of gear trains to solve such problems and we propose a genetic algorithm based gear design system.

M. Chandrasekaran: Gears are used in almost all mechanical devices and they do several important jobs, but most important, they provide a gear reduction. This is vital to ensure that even though there is enough power there is also enough torque. Gear box has to produce maximum power with minimum weight. In many real-life problems, objectives under consideration conflict with each other, and optimizing a particular solution with respect to a single objective can result in unacceptable results with respect to the other objectives. Multi-objective formulations are realistic models for many complex engineering optimization problems.

2.2 FuzzyModelling and Optimization:

A. Chaibakhsh: In this paper, an application of a neuro-fuzzy modeling approach is presented in order to characterize the essential behavior of enzymatic esterification processes. The accuracy of the developed model was validated by comparing the response of the model and actual experimental data. The simulation results showed good generalization of the proposed model and its ability to predict the reaction yield, where the error of prediction for training data was less than 3%, and for validating and testing data less than 3 and 1.5%, respectively. A model-based optimization was performed to obtain the best operating conditions by using genetic algorithm. A fair comparison between the optimization results obtained from simulation experiments and laboratory data indicated the accuracy and feasibility of the proposed approach for estimating the optimal profiles in biotechnological processes. This can further facilitate up-scaling of the process by selecting the appropriate combinations of potential manufacturing parameters.

3. DESIGN METHODOLOGY

A heavy duty helical gear pair is considered. Data used are: power to be transmitted = 120 kW, gear ratio = 5.18, pressure angle = 20°, helix angle = 12°, material is case hardened steel (20MnCr5). Using Lewis equation, module is obtained as 14mm. DIN Standards [12, 13] and parameters for pinion, wheel and strength based factors are considered [8]. MATLAB solvers fmincon and GA are used for performing design optimization. In this procedure, module m_n (or x_1), face width, mm (b or x_2), gear teeth on drive and driven (Z_1 or x_3), (Z_2 or x_4) and helix angle, deg (β or x_5) are used as design variables.Upper and lower bounds of design variables are: $14 \leq m_n \leq 15$, $50 \leq b \leq 250$, $25 \leq Z_1 \leq 56$, $130 \leq Z_2 \leq 290$, $4^o \leq \beta \leq 19.5^o$.

- **Objective function**

Gear can be designed either on the basis of minimum centre distance, or minimum weight. Here we are designing a gear on the basis of minimum volume. It is required to minimize the volume because smaller gears are easy to design, requires less material, less space and will run smoothly due to smaller inertial loads.
The volume of the gear train is given by

$$V = \frac{\pi}{4}\frac{m_n^2\, b(Z_1^2+Z_2^2)}{Cos^2\beta}$$

The objective function can be written as

$$F(x) = V = f(m_n, b, Z_1, Z_2, \beta) = f(x_1,x_2,x_3,x_4,x_5) = \frac{\pi}{4}\frac{m_n^2\, b(Z_1^2+Z_2^2)}{Cos^2\beta}$$

- **Constraints**

Following constraint are taken in study bending stress, compressive stress, normal module, gear ratio, centre distance between pinion & gear and factor of safety from pitting constraints.

Condition of bending stress:

Failure in bending is generally catastrophic; hence appropriate care in the designing process is prudent and appropriate. To avoid tooth breakage, the bending stress should be limited to the maximum allowable bending stress of the material. The induced bending stress in an involute gear is calculated from the formula.

The induced bending stress is represented below

$$\sigma_b = 0.7\frac{(i+1)}{(a\, m_n b\, y_v)} \times [M_t]$$

$$\sigma_b \leq [\sigma_b]_{al}$$

$$[Mt] = M_t \times k \times k_d$$

Condition of compressive stress:

The induced Compressive stress is represented

$$\sigma_c = 0.7\left(\frac{i+1}{a}\right) \times \sqrt{\frac{i+1}{ib} \times E \times [M_t]}$$

$$\sigma_c \leq [\sigma_c]_{al}$$

Normal Module

$$m_{min} = 1.15\, cos\beta \times \sqrt[3]{\frac{[M_t]}{(y_v[\sigma_b]\Psi_m Z_1)}}$$

$$m_n \geq m_{min}$$

Gear Ratio:

Gear ratio constraint is represented below

$$i = \frac{Z_2}{Z_1} = 2$$

Centre distance between Pinion and Gear:

The minimum center distance is represented

$$a \geq a_{min}$$

$$a = \frac{m_n}{2cos\beta}[Z_1 + Z_2]$$

$$a_{min} = (i+1) \times \sqrt[3]{\left(\frac{0.7}{[\sigma_c]}\right)^2 \times \left(\frac{E[M_t]}{i\Psi}\right)}$$

$$\Psi = \frac{b}{a}$$

Factor of safety from pitting constraints:
In our work we have introduce this constraints. Pitting is a fatigue failure of a material commonly seen in gears. Pitting occurs when fatigue cracks are initiated on the tooth surface or just below the surface. Constraints of pitting are deduced from contact stress, elasticity, contact ratio and poison's ratio for pinion and wheel. They are as follows:-

$$g_1(x) = 1.2 - \frac{1261.82}{189.81 \times \sqrt{\frac{1}{\varepsilon_{\alpha1}+\varepsilon_{\alpha2}}} \times \sqrt{\cos x_5} \times 38.251 \times \sqrt{\frac{1}{x_2}} \times 1.14} \leq 0$$

$$g_2(x) = 1.2 - \frac{1262.44}{189.81 \times \sqrt{\frac{1}{\varepsilon_{\alpha1}+\varepsilon_{\alpha2}}} \times \sqrt{\cos x_5} \times 38.251 \times \sqrt{\frac{1}{x_2}} \times 1.14} \leq 0$$

Where:
$\varepsilon\alpha_1$= Transverse contact ratio for pinion
$\varepsilon\alpha_2$= Transverse contact ratio for wheel

4. WORKING PRINCIPLE OF GENETIC ALGORITHM

Genetic algorithm maintains a population of individuals, say P (t), for generation t. Each individual represents a potential solution to the problem at hand. Each individual is evaluated to give some measure of its fitness. Some individuals undergo stochastic transformations by means of genetic operations to form new individuals. There are three steps:-

- Selection, which selects the best chromosomes according to their fitness values.
- Crossover, which creates new individuals by combining parts from two individuals. A new population is formed by selecting the more fit individuals from the parent population and offspring population.
- Mutation, which creates new individuals by making changes in a single individual.

After several generations, genetic algorithm converges to the best individual, which hopefully represents an optimal or suboptimal solution to the problem.

5. STEPS IN BASIC GENETIC ALGORITHM

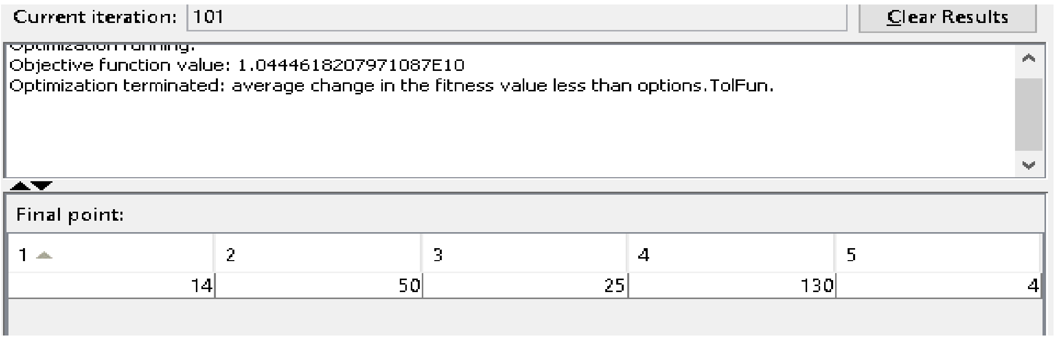
1. [Start] Define the fitness function f(x) according to the problem definition.
2. [Initialise] Generate random population of n chromosomes – each chromosome being the potential solution.
3. [Fitness] Evaluate the fitness f(x) of each chromosome x in the population.

4. [New population]Repeat the following steps to create the new population of chromosomes:
    a. [Selection] Select some parent chromosomes from a population according to their fitness to form mating pool.
    b. [Crossover] Mate the selected chromosomes as per given crossover probability to form new off-springs.
    c. [Mutation]Mutate new chromosomes as per given mutation probability.
    d. [Replace] Replace the old population of chromosomes with the new population.
5. [Convergence check] If the maximum number of generations is reached, then stop, and return the best solution. 6. [Loop] Go to step 3.

6. GA RESULTS

The procedure described in the previous sections has been applied to the design helical gear pair. It presents an approach for combining mechanical component design models with non-traditional optimization techniques namely Genetic algorithms and Fmincon procedures. It is shown that the problem may be posed as a non-linear optimization problem, wherein the fitness function changes over successive generations. Results are presented for the optimal design problem of a helical gear set, where its volume as the objective functions is subjected to constraints.

Table 6.1 shows the results recorded after implementing the optimization process on the input data. The MATLAB program for GA has been run on i7 Intel(R) Core(TM) processor with 4 GB RAM and 64-bit operating system. Overall, 100, 200 300, 350 and 500 generations are experimented to check the validity of results.



Current iteration: 101

```
Optimization running.
Objective function value: 1.0444618207971087E10
Optimization terminated: average change in the fitness value less than options.TolFun.
```

Final point:

1	2	3	4	5
14	50	25	130	4

Fig. 6.1: Optimised results at 100 iteration

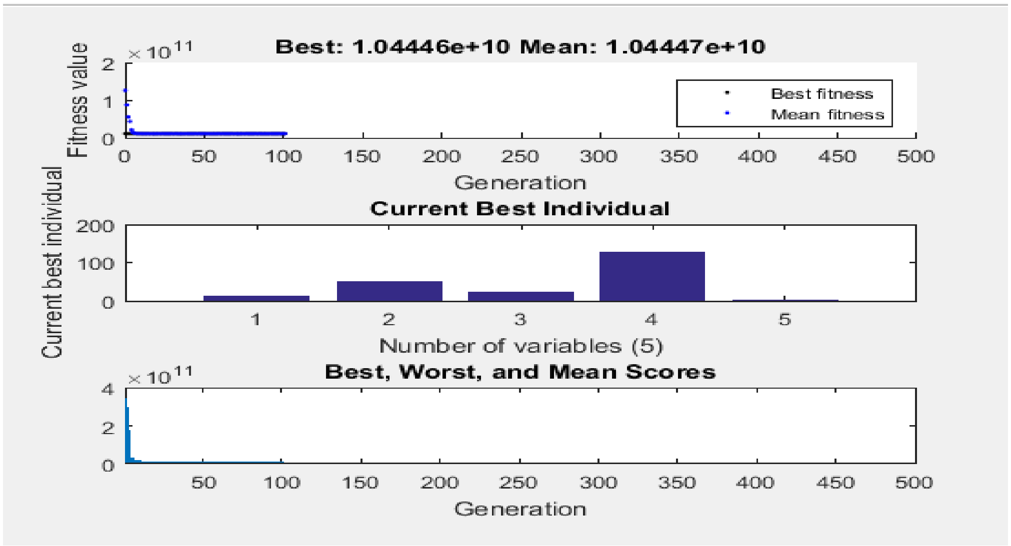
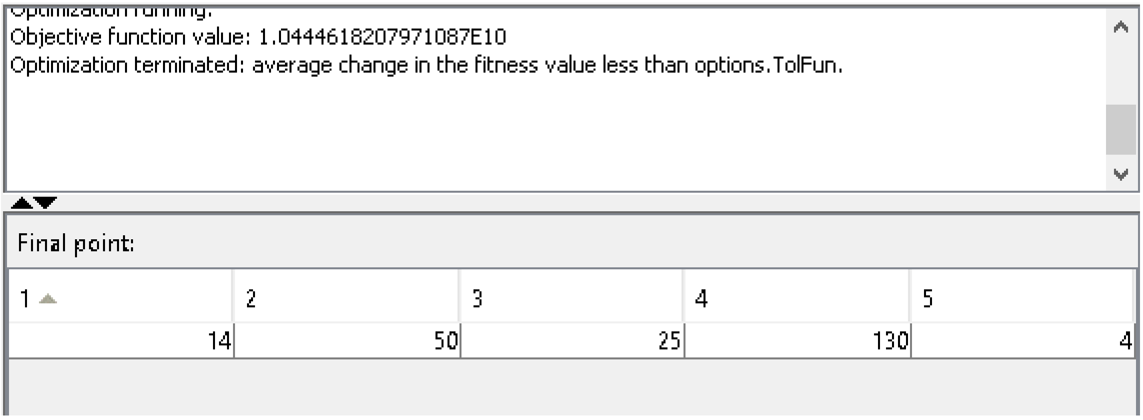


Fig. 6.2: Function value at 100 iteration



```
Optimization running.
Objective function value: 1.0444618207971087E10
Optimization terminated: average change in the fitness value less than options.TolFun.
```

Final point:

1	2	3	4	5
14	50	25	130	4

Fig. 6.3: Optimised results at 200 iteration

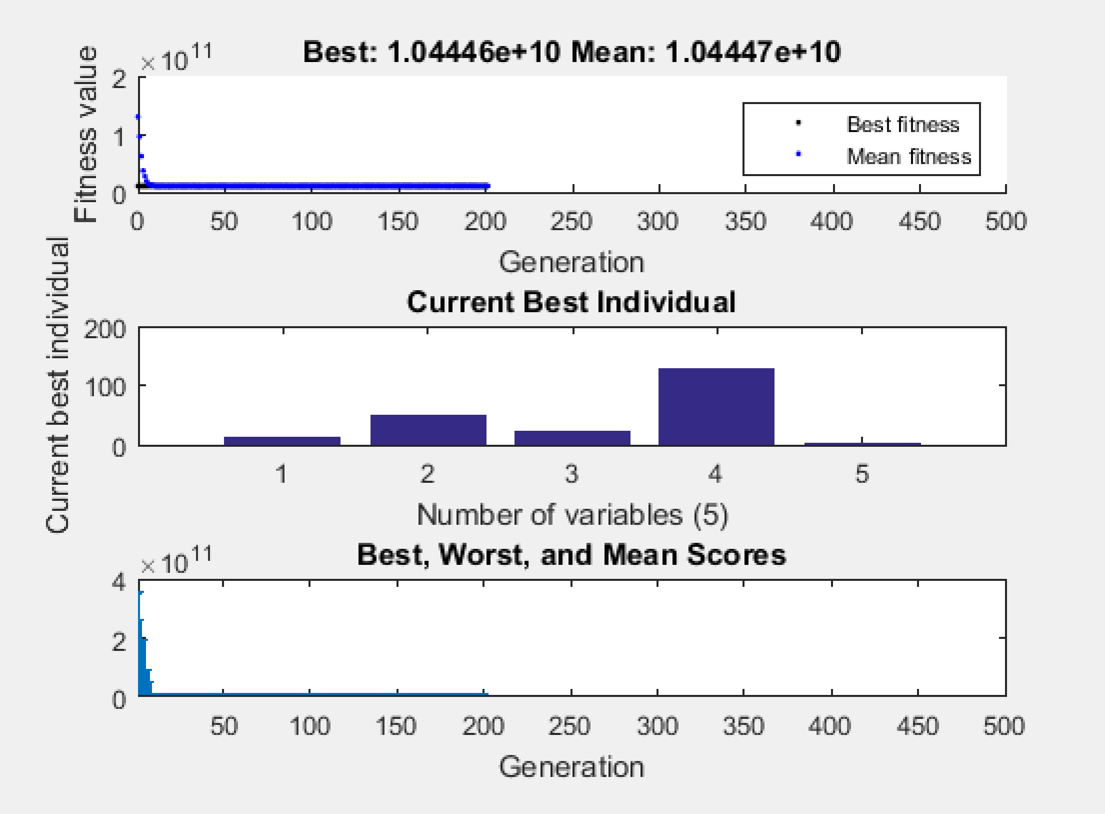
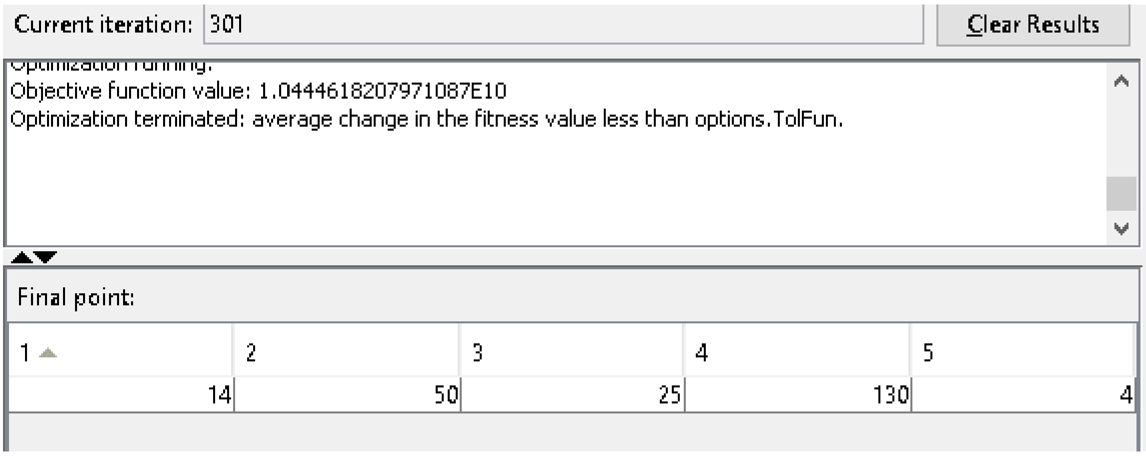


Fig. 6.4: Function value at 200 iteration



Current iteration: 301

```
Optimization running.
Objective function value: 1.0444618207971087E10
Optimization terminated: average change in the fitness value less than options.TolFun.
```

Final point:

1	2	3	4	5
14	50	25	130	4

Fig. 6.5: Optimised results at 300 iteration

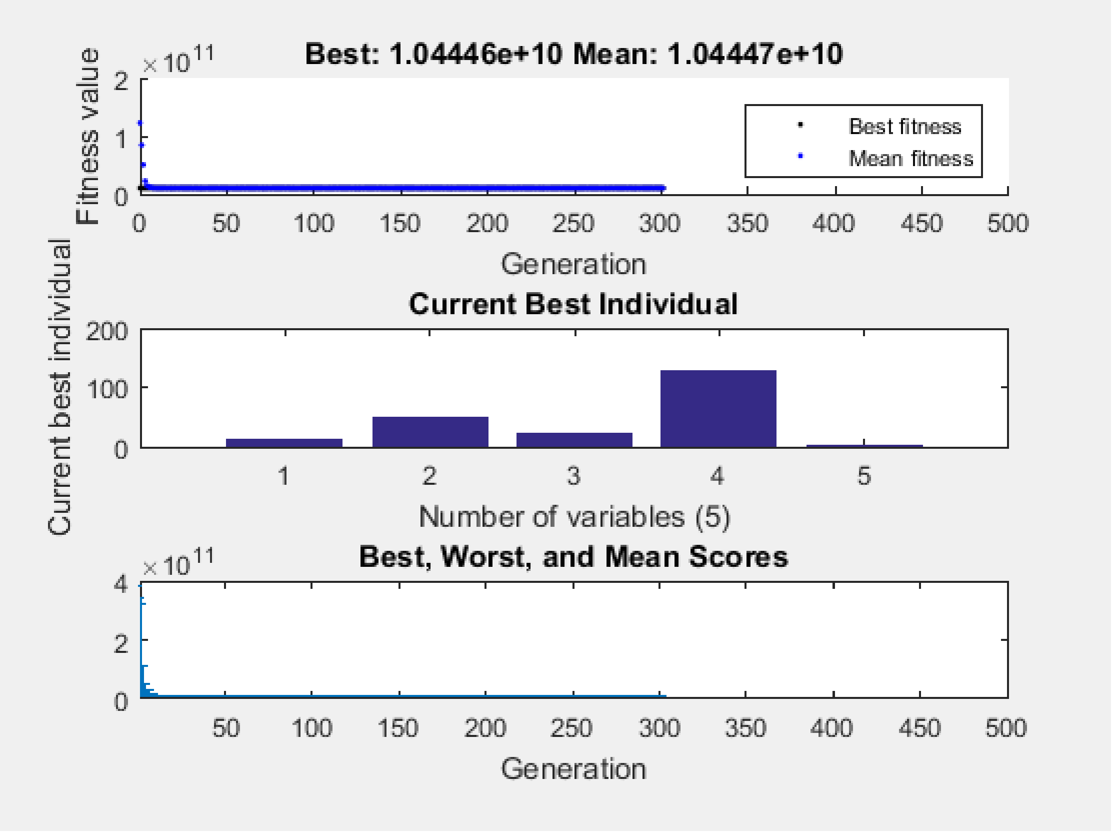
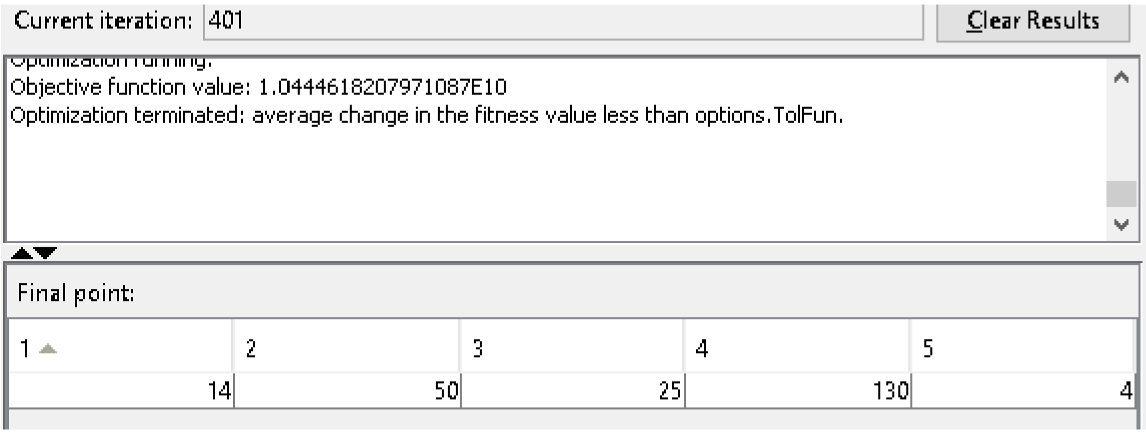


Fig. 6.6: Function value at 300 iteration



Current iteration: 401

```
Optimization running.
Objective function value: 1.0444618207971087E10
Optimization terminated: average change in the fitness value less than options.TolFun.
```

Final point:

1	2	3	4	5
14	50	25	130	4

Fig. 6.7: Optimised results at 400 iteration

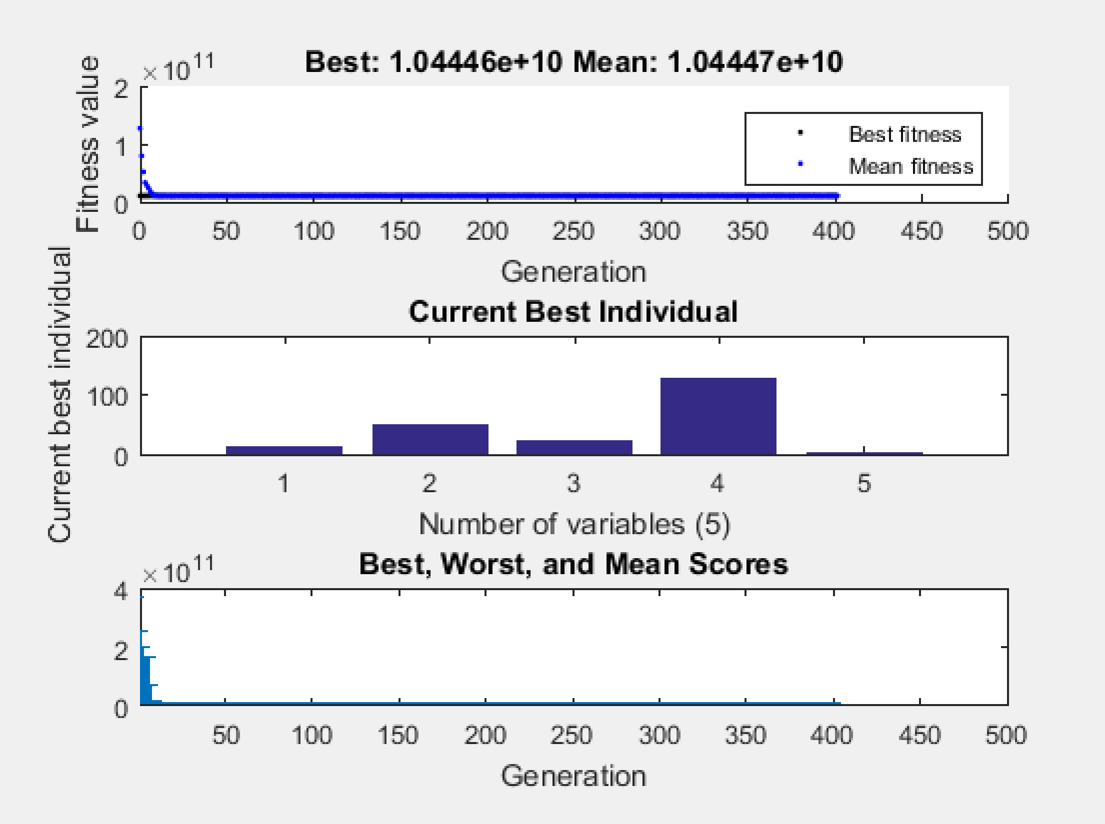
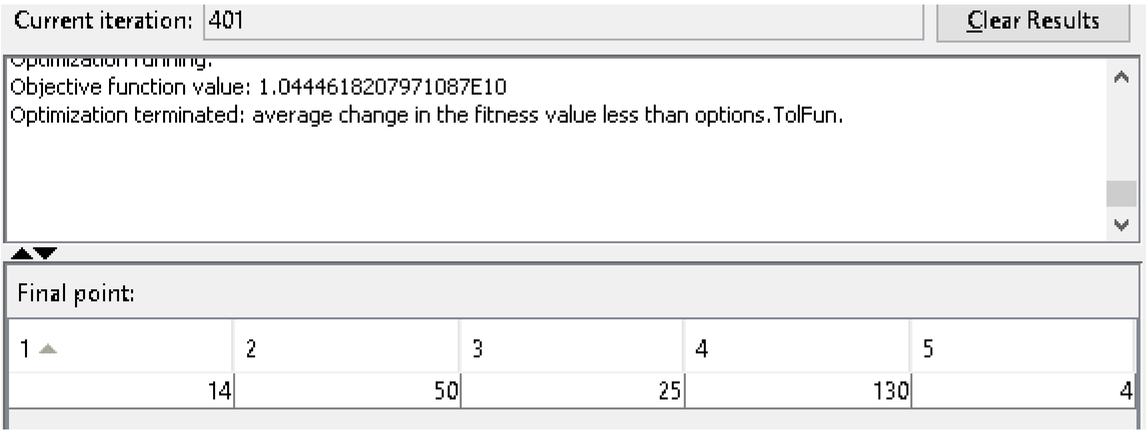


Fig. 6.8: Function value at 400 iteration



Current iteration: 401

```
Optimization running.
Objective function value: 1.0444618207971087E10
Optimization terminated: average change in the fitness value less than options.TolFun.
```

Final point:

1	2	3	4	5
14	50	25	130	4

Fig. 6.9: Optimised results at 500 iteration

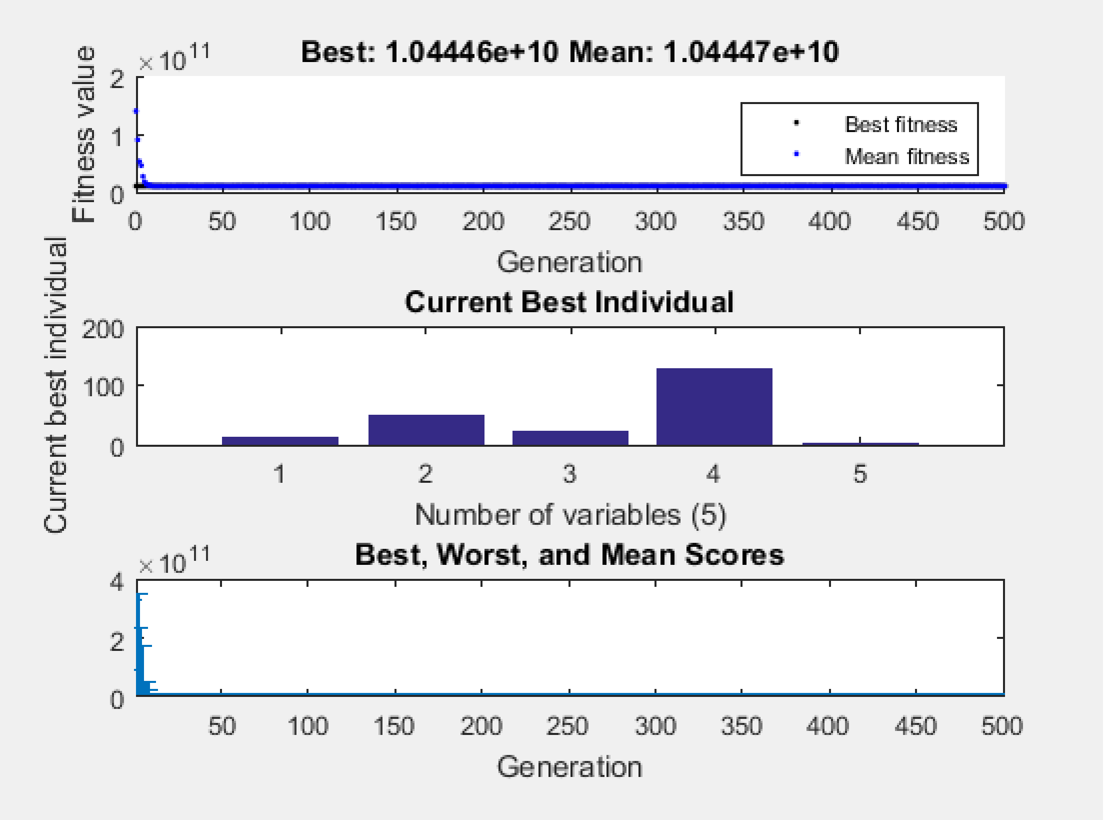


Fig. 6.10: Function value at 500 iteration

From below table shows that after 100, 200, 300, 400 and 500 simulation value of volume and other decision variables are optimized.

Table 6.1: Genetic algorithm results

Module(mm)	Face width (mm)	No. of Teeth on pinion	No. of Teeth on gear	Helix angle (degree)	Volume (mm^3)
14	50	25	130	4	1.044 x 10^{10}

From above table value of decision variable should be taken such as module (m_n) = 14 mm, face width (b) = 50 mm, No. of teeth on pinion (Z_1) = 25, No. of teeth on gear (Z_2) = 130 and Helix angle (β) = 4°. Value of objective function that is volume = 1.044 x 10^{10} mm^3.

6.2 Fmincon matlab results

Table 6.2 shows the results recorded after implementing the optimization process on the input data. The MATLAB program for FMINCON has been run on i7 Intel(R) Core(TM) processor with 4 GB RAM and 64-bit operating system.

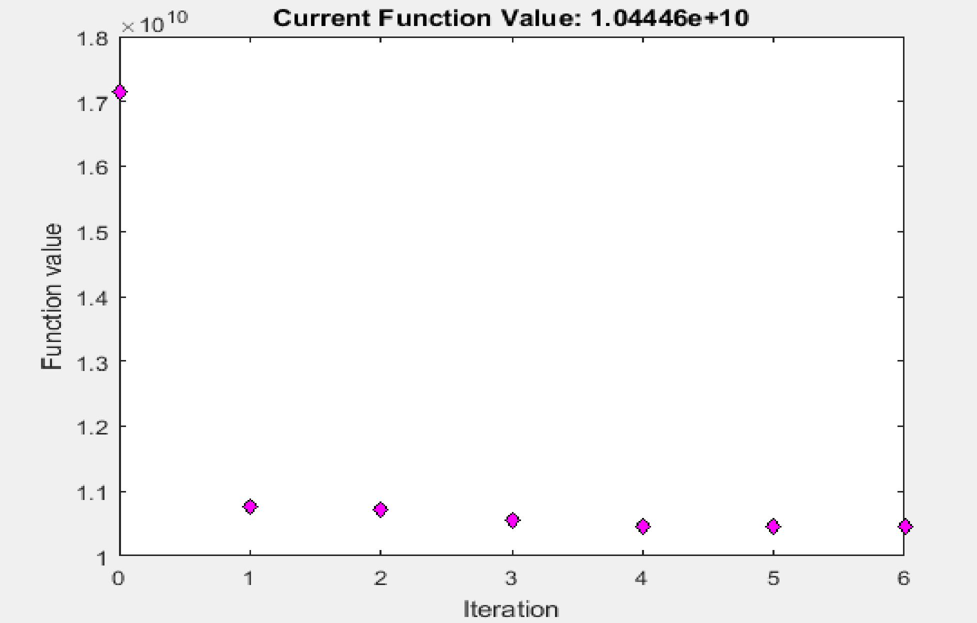
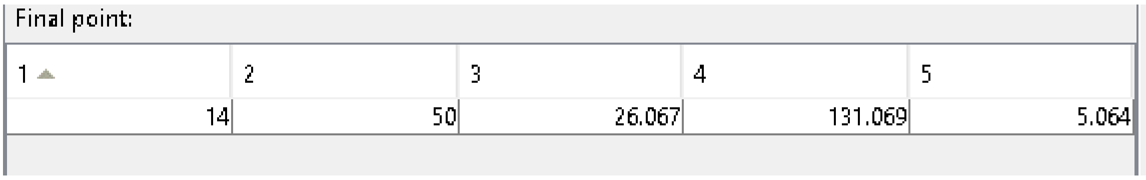


Fig. 6.11: Function value after implementing FMINCON



Final point:

1	2	3	4	5
14	50	26.067	131.069	5.064

Fig. 6.12: Optimum value after implementing FMINCON

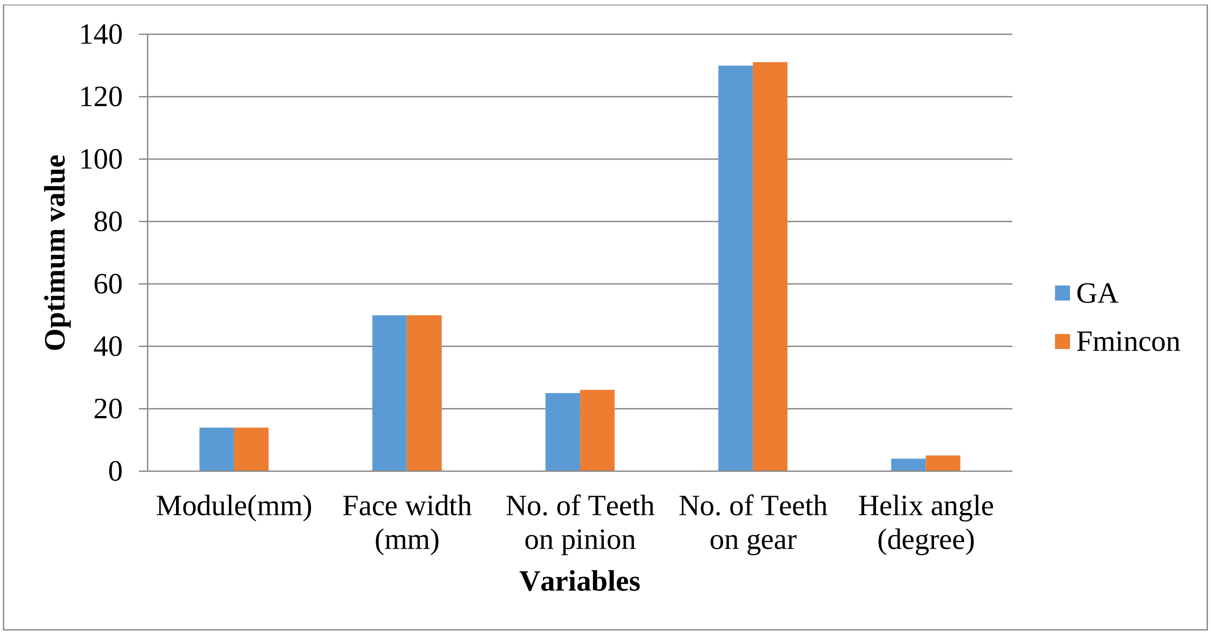


Fig. 6.13: Comparison of results obtained

7. CONCLUSION

In this work, a heavy duty helical gear pair is optimized. Objective functions and all constraints are well satisfied. Nature inspired algorithms GA and MATLAB solvers fmincon are successfully applied. The following are the important findings:

1. Results obtained by genetic algorithm technique for all generations are almost same for our problem.
2. By using GA value of decision variable is module (m_n) = 14 mm, face width (b) = 50 mm, No. of teeth on pinion (Z_1) = 25, No. of teeth on gear (Z_2) = 130 and Helix angle (β) = 4º. Value of objective function that is volume = 1.044 x 10^{10} mm^3.
3. By using Fmincon value of decision variable is module (m_n) = 14 mm, face width (b) = 50 mm, No. of teeth on pinion (Z_1) = 26, No. of teeth on gear (Z_2) = 132 and Helix angle (β) = 5º. Value of objective function that is volume = 1.044 x 10^{10} mm^3.
4. ParidhiRai et al. (2018) minimized the volume of helical gear pair by including profile shaft coefficients as design variables along with module, face width and number of teeth using RCGA and optimized volume achieved is 5.50560 x 10^{10} mm^3. However in our work we have used two techniques namely GA and fmincon and our improved optimised results are 1.044 x 10^{10} mm^3.
5. GA algorithm gives the best results for all design variables and objective function in helical gear design.

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